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Level formation and disclosure of normal cracks in reinforced concrete elements and structures

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Abstract

The article is devoted to the study of the main regularities of the normal cracks level formation in reinforced concrete elements and structures. A critical analysis of the latest publications related to the theme of these studies has been carried out. The main characteristics of prototypes, the conditions for their manufacture and storage are given. Based on the experimental studies results, it has been established that in the real design of bending reinforced concrete elements, when calculating their crack resistance, one can restrict oneself to only two levels of normal cracking. A statistical comparison of the calculation results using the author's and other methods with experimental data confirmed the effectiveness of those calculation methods in which the crack formation step is directly related to the basic laws and parameters of reinforcement to concrete adhesion.

Keywords: Reinforced concrete, elements, adhesion, reinforcement, cracks, levels of formation, step, width.

1. Introduction

In general, it is known that the processes of cracks formation and development, including normal ones, significantly affect the operational properties of reinforced concrete elements and structures. Therefore, it is quite obvious that the issues of their crack resistance will always remain one of the main issues in the reinforced concrete deformation theory. And with the introduction of deformation methods for calculating reinforced concrete elements

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and structures into modern design practice, they acquire even greater weight and relevance. Indeed, using deformation models, it becomes possible to more accurately reproduce the real stress-strain state of reinforced concrete elements and structures in their deformation process.

At the same time, the results of experimental studies indicate that the cracks formation and development in reinforced concrete elements is multilevel and leads to a gradual disruption of the reinforcement with tensioned concrete interaction. Under such circumstances, it would be advisable to build a general methodology for calculating the normal cracks formation and opening on the basis of the reinforcement to concrete adhesion defining laws direct involvement. Otherwise, the calculation of the normal cracks opening width according to the Thomas (1936) hypothesis will continue to remain predominantly declarative. This is due to the fact that it is extremely difficult to perform this calculation from the standpoint of the concrete and reinforcement mutual displacements sequential accumulation. Since the actual dependence of the reinforcement and concrete mutual displacements is very complex and cannot be described by a single function, its direct integration in most cases is practically impossible. However, the calculation of the normal cracks opening width can be significantly simplified if the cracks step and their opening width are directly related to the reinforcement to concrete adhesion forces and take into account that the cracking process is multilevel. Therefore, the possibility and expediency of such an approach to the calculation of the main parameters of reinforced concrete elements and structures crack resistance requires special studies.

Nomenclature

M	bending moment
N_{ct}	forces in tensioned concrete
N_{bd}	adhesion forces of reinforcement to concrete
τ_b	adhesion stresses of reinforcement with concrete
f_{ct}	tensile concrete strength
σ_s	reinforcement stresses
ε_s	reinforcement deformations
s_r	cracking step
w	crack opening width

2. Analysis of basic research and publications

Usually investigation of reinforced concrete elements and structures crack resistance is devoted to a lot of works by domestic, and even more foreign scientists. However, only a few of them were aimed at identifying general patterns of normal cracks real level formation and development, taking into account the reinforcement to concrete adhesion. They can be conditionally divided into 4 following directions.

In the first direction works, the effect of reinforcement to concrete adhesion on the normal cracks formation and development sequence is modeled by direct integration of concrete and reinforcement mutual displacement diagrams of (Alvarez (1998), Fernández Ruiz et al. (2005) and Rudny (2015)). However, it is extremely difficult to implement this method in practical calculations, since the shape of these diagrams in the process of reinforced concrete elements deformation is constantly changing (Eligehausen et al. (1983), Shima et al. (1987) and Harajli et al. (1995)), which makes their direct integration practically impossible.

Therefore, the works of the second direction (Karpenko (1996), Veselov (2000), Benin et al. (2013), Shardakov et al. (2016)) are mainly aimed at numerical methods for calculating normal cracks multilevel formation and opening. Their implementation is possible only by finite element methods using special software systems. Quite often, this leads to the fact that the engineering visibility and the physical essence of the processes of reinforcement to concrete adhesion and cracking in a reinforced concrete element are partially lost or leveled.

In studies of the third direction, a special "two-console" element is used (Kolchunov and Yakovenko (2009), Yakovenko (2018)). The technique built with its help, in general, allows simulating the normal cracks level formation. But today its implementation in practical calculations is still quite difficult because of the great difficulties associated with the "isolation" or formation of the "two-console" element itself, and therefore it is possible only with the help of special computer programs.

In the works of the 4th direction, the methods for calculating the normal cracks level formation are constructed using the general function of the average stresses of reinforcement to concrete adhesion (Kochkarev (2018), Romashko and Romashko (2018)). They are quite simple to implement in practical calculations. However, the question remains about the validity of the connection (linear or nonlinear) form between the average values of the reinforcement with concrete adhesion stresses and the average values of normal stresses in the reinforcement itself at all stages of reinforced concrete element deformation.

3. Purpose and objectives of research

These studies were aimed at experimental and theoretical substantiation of the connection (linear or nonlinear) form between the average values of reinforcement with concrete adhesion stresses and average values of normal stresses in the reinforcement itself.

To achieve this goal, the tasks were set to investigate the regularities of the normal cracks formation level and opening in bending elements by testing reinforced concrete beams, to calculate by different methods the normal cracks opening width during their formation level, to carry out the corresponding statistical comparisons of the obtained calculation results with experimental data.

4. Research results

In order to solve the above problems, it was decided to manufacture and test three reinforced concrete beams 2000 mm long with a cross-sectional size of 200x100 mm. In the lower stretched zone, the beams were reinforced with two longitudinal rods with a diameter of 10 mm class A500C. Transverse rods with a diameter of 4 mm made of B500 class reinforcement in the form of bent closed clamps were installed on the support sections, outside the pure bending zone. They were placed with a step of 100 mm. The upper structural rods in this area were also 4 mm in diameter from the B500 class reinforcement (Fig. 1). The concrete cover for the top and bottom reinforcement was the same and was 12 mm.

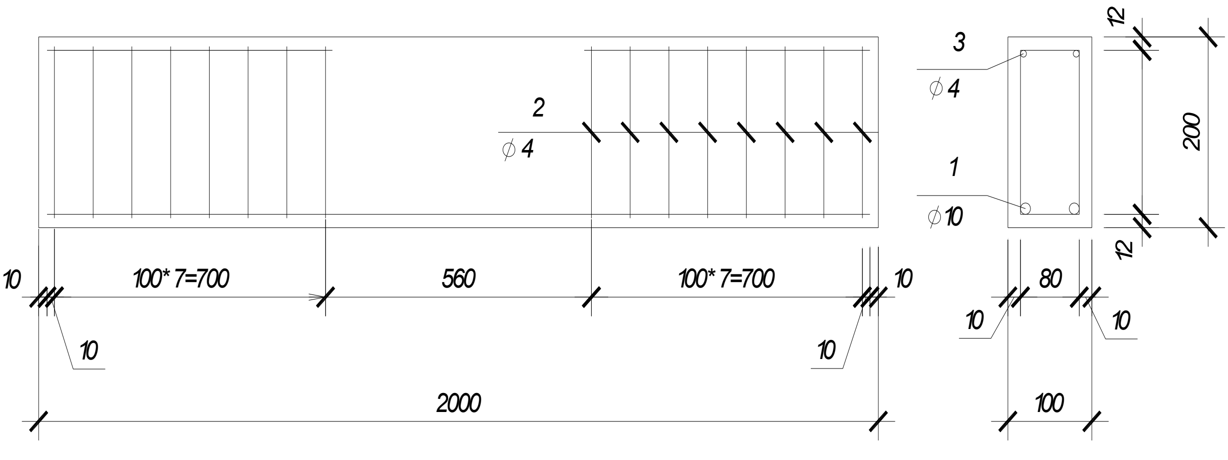

Fig. 1. Design and reinforcement scheme of reinforced concrete beams.

All beams were made of C20 / 25 class heavy concrete. The concrete mixture preparation and the prototypes formation were carried out in laboratory conditions. Their concreting was carried out in special metal molds in a horizontal position. The concrete mix was compacted on a special vibrating platform. Concrete hardening took place under normal environmental conditions in the scientific laboratory of the Department of Industrial, Civil

Engineering and Engineering Structures. All prototypes preparation for testing began when they reached 28 days of age.

The beams tests were carried out in a special frame installation according to the scheme of a single-span beams hinged on the supports with a span of 1800 mm. To set up a pure bending zone, they were loaded with two concentrated forces in the middle third of the calculated span through a distribution metal traverse. The load was created using a 15-ton hydraulic jack and a manual pump station and was controlled by a calibrated ring dynamometer.

The deflections of the beam and its subsidence on the supports were controlled using 6PAO deflection meters. Compressed concrete deformations were measured using 1MIG indicators, which were installed with a measurement base of 200 mm in the beam middle part. The bottom reinforcement deformations were controlled using conventional Hugenberger strain gauges installed in the middle of the beam span on each of the tension rods. The onset and normal cracks development in the beams were recorded visually, and their opening width was examined using an MPB-3 microscope with a scale division of 0.02 mm.

The beams were loaded in steps equal to about 1/10 of the theoretical bearing capacity (M_u). In order to fix the first cracks formation, the value of the 4 initial load stages was reduced to 1/20 of M_u. To fix the moment of the beams bearing strength loss, the two final stages of their loading were taken the same.

The experimental results obtained by Romashko-Maistruk (2021) have confirmed that the process of normal cracks formation in reinforced concrete beams is in fact a multilevel process (Fig. 2).

The first cracks in the beams were formed at the 3rd or the 4th loading stages at bending moments $M_{w.1} \approx (0.125...0.17)M_u$. Their step was equal to (80...205) mm, and the opening width was (0.02...0.05) mm.

Cracks of the second level appeared at the 6th or the 7th load steps at bending moments $M_{w.2} \approx (0.33...0.5)M_u$. The step between them was already (60...105) mm, and the opening width of the main cracks reached (0.09...0.13) mm. It was noted that with the formation of second-level cracks, the intensity of their opening at first slightly decreased, and then increased again.

Level 3 cracks began to appear at the 9th to12th loading stages at bending moments $M_{w.3} \approx (0.78...0.95)M_u$, that is, shortly before or during the reinforcement flow. The distance between normal cracks decreased to (30...70) mm, and their opening width increased to (0.17...0.22) mm.

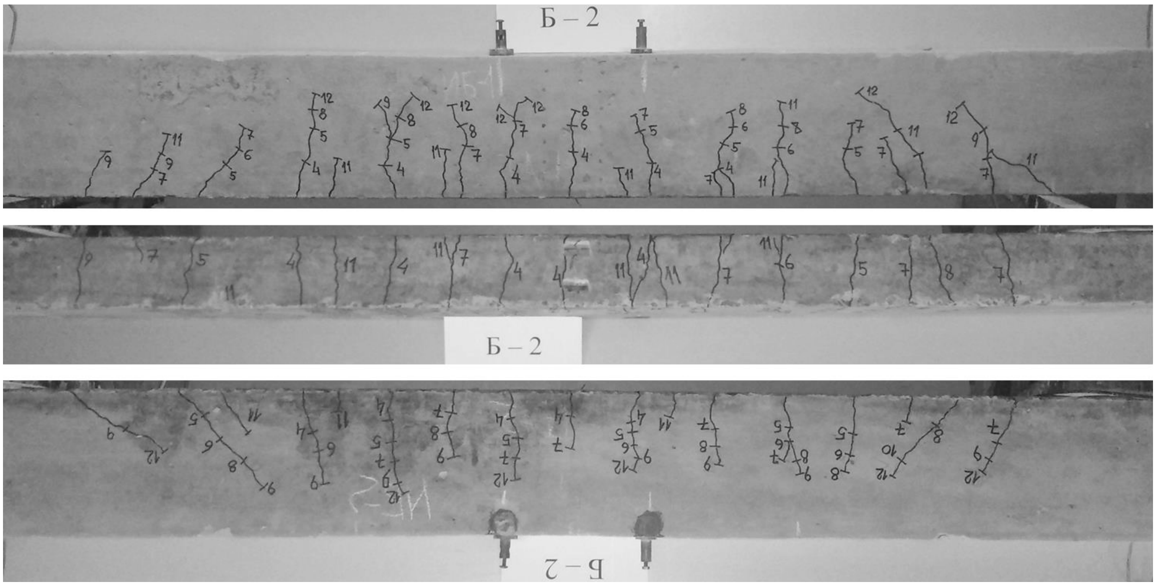

Fig. 2. Scanning the formation and development of cracks in the beam B-2.

Taking into account the experimental studies results, the theoretical values of the main normal cracks opening width in the beams were calculated according to the scheme of a two-level formation (Romashko and Romashko (2019)) according to the dependence:

$$w_k = s_{r1}(\varepsilon_{sm} - \varepsilon_{ctm}) - s_{r2}(\varepsilon_{sm} - \varepsilon_{sm,cr2} - \varepsilon_{ctm}), \tag{1}$$

where s_{r1} and s_{r2} is the step between adjacent cracks at the 1st and 2nd levels of their formation; ε_{sm} - the value of the tensile reinforcement average strains in the area between adjacent normal cracks; ε_{ctm} - average deformations of tensile concrete in the same area; $\varepsilon_{sm,cr2}$ - average deformations of tensile reinforcement in the most stressed section between adjacent cracks at the moment of the second level cracks appearance.

All of the above deformations were determined according to the deformation-force model (Romashko and Romashko (2019)) according to the solution of the well-known simplest relationships system in the mechanics of a deformable solid (MDS):

$$\left.\begin{array}{ll} \text{static} & M = f(\varepsilon_c, \varepsilon_{ct}, \varepsilon_s), \quad N = f(\varepsilon_c, \varepsilon_{ct}, \varepsilon_s); \\ \text{geometric} & 1/r = f(\varepsilon_c, \varepsilon_{ct}, \varepsilon_s); \\ \text{physical (state of materials)} & \sigma_c = f(\varepsilon_c), \sigma_{ct} = f(\varepsilon_{ct}), \sigma_s = f(\varepsilon_s). \end{array}\right\} \tag{2}$$

The distance between the corresponding level cracks was determined by the equilibrium of the maximum possible forces in tensile concrete $N_{ct,cr} = f(\varepsilon_{ctu})$ and the forces of reinforcement to concrete active adhesion $N_{bd,cr}$ in the area between the indicated cracks ((Romashko and Romashko (2018))) according to the expression:

$$s_{ri} = \frac{\varnothing_s}{4 \cdot \tau_{bmi} \cdot \rho_{l,t}}, \tag{3}$$

where $\varnothing_s$ is the diameter of the working reinforcement bars; τ_{bmi} - the value of the average reinforcement with concrete adhesion stresses in the area between adjacent cracks of the corresponding level; $\rho_{l,t}$ is the coefficient of reinforcement of the stretched zone of a reinforced concrete element ($\rho_{l,t} = A_s / A_{ct,cr}$).

Average reinforcement with concrete adhesion stresses were taken according to the generalized nonlinear function of the authors Romashko and Romashko (2018):

$$\tau_{bmi} = \eta_1 \cdot \eta_2 \cdot f_{ctk} \cdot (\sigma_{si} / f_{yk})^{1-1/\eta_1} \tag{4}$$

and by the linear function Kochkarev (2018):

$$\tau_{m,i} = f_{ctm} \cdot \left(\frac{\eta_1 \cdot \eta_2 - \alpha_0}{f_{yd}} \cdot \sigma_{si} + \alpha_0 \right), \tag{5}$$

where η_1 is the coefficient taking into account the reinforcement profile the according to the adhesion index, is taken according to Romashko-Maistruk (2021); η_2 - coefficient taking into account the reinforcement diameter the; f_{ctk} and f_{ctm} - characteristic and average value of concrete strength under axial tension; σ_{si} - the maximum normal stresses in the reinforcement in the area of its active adhesion to tensile concrete, at which cracks of a certain level appear ($\sigma_{si} = \sigma_{s,cri}$); $\sigma_{si} = \sigma_{s,cri}$ - the maximum possible stresses in tensile reinforcement in the area of its active adhesion to tensile concrete (cannot exceed the limit values f_{yk}); α_0 - coefficient of proportionality between the initial stresses of reinforcement to concrete adhesion and stresses in tensile concrete.

In addition, the calculations were carried out according to the traditional schemes of "one-level" normal cracks formation in accordance with the current norms DSTU B V.2.6-156:2010 (2011), EN 1992-1-1 (2004) and building rules SP 63.13330.2012 (2013), as well as according to the simplified method Romashko and Romashko (2018), in which instead of the nonlinear function (4), fixed averaged values were used medium stresses of reinforcement to concrete adhesion. They were calculated using a rather simple expression:

$$\tau_{bm} = \eta_1 \cdot \eta_2 \cdot f_{ctk} / 2 . \tag{6}$$

The graphs of the experimental and theoretical values of the crack opening width calculated using the above methods are shown in Fig. 3, and the main statistical characteristics of their comparison are listed in table 1.

Thus, the above studies results carried out clearly demonstrate that in the real design of reinforced concrete elements and structures, those methods that take into account the normal cracks level formation will have an advantage.

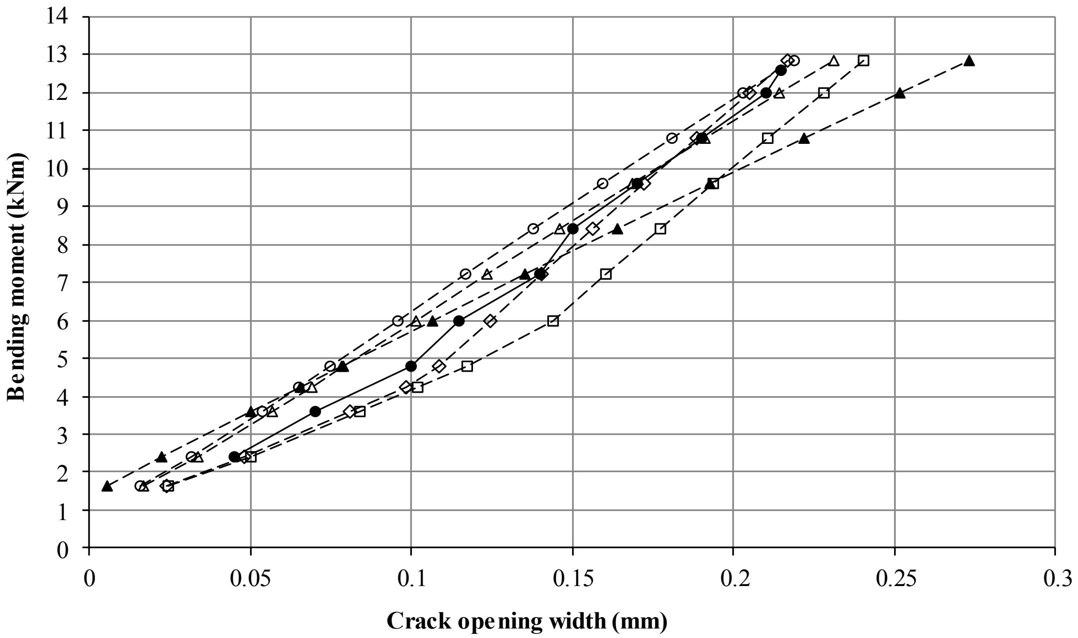

Fig. 3. Dependence of crack opening width (w_m) on bending moments (M) in beam B-3: ● - experimental; theoretical according to the methodology: △ - DSTU B V.2.6-156:2010 (2011) and EN 1992-1-1 (2004), ▲ - SP 63.13330.2012 (2013), □ - Kochkarev (2018), ◇ - Romashko-Maistruk (2021), ○ - Romashko and Romashko (2018).

Table 1. Statistical evaluation of methods for calculating the normal cracks opening width in beams B-1 ... B-3.

Method of calculation	Deviations from experimental data		Coefficient of variation v_w , %
	arithmetic mean Δ_w , %	root mean square σ_w , %	
DSTU B V.2.6-156:2010 (2011) and EN 1992-1-1 (2004)	7.62	10.74	11.58
SP 63.13330.2012 (2013)	3.0	23.14	23.87
Kochkarev (2018)	16.04	5.17	4.46
Romashko-Maistruk (2021)	5.0	6.6	6.29
Romashko and Romashko (2018)	12.93	9.57	10.99

5. Conclusion

In the real design of bending reinforced concrete elements and structures, when calculating their crack resistance, it is sufficient to be limited to only 2 levels of normal cracking. Methods for calculating crack resistance, built with the involvement of the reinforcement to concrete adhesion basic laws, make it possible to more accurately reproduce the real process of normal cracks formation and opening in reinforced concrete elements. The process of normal cracks level formation in reinforced concrete elements can be relatively easily controlled using the average bond stress function between reinforcement and concrete. The nonlinear function of the average adhesion stresses between reinforcement and concrete allows one to more accurately determine the main parameters of the normal cracks formation and opening in comparison with the linear one. In the future, it would be advisable to investigate the effect of prestressing on the process of normal cracks level formation and opening.

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